

NASA'S HUMAN MISSION TO A NEAR-EARTH ASTEROID: LANDING ON A MOVING TARGET

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ABSTRACT

This paper describes a Bayesian approach for comparing the productivity and cost-risk tradeoffs of sending versus not sending one or more robotic surveyor missions prior to a human mission to land on an asteroid. The expected value of sample information based on productivity combined with parametric variations in the prior probability an asteroid might be found suitable for landing were used to assess the optimal number of spacecraft and asteroids to survey. The analysis supports the value of surveyor missions to asteroids and indicates one launch with two spacecraft going simultaneously to two independent asteroids appears optimal.

INTRODUCTION

NASA's recent attention and interest in sending a human mission to land on a Near-Earth asteroid raised a number of issues [3] [4]. A critical question was whether the asteroid would be suitable for a human landing and whether the cost-versus-risk reduction of first sending a robotic surveyor would be justified prior to the larger, more complex human mission. One alternative would send the human mission directly to an asteroid and use real-time analysis on arrival to evaluate and plan a “landing” on the surface. Alternatively, one or more surveyor missions could be sent prior to the human mission to conduct “close-up” observations to determine the feasibility of landing. This paper uses a Bayesian approach to compute the expected value of sample information (EVS) in the form of the expected value of “suitability” information provided by a surveyor versus a direct mission without suitability information.

Orchestrating a human “landing” on an asteroid is complex because asteroids are generally not spherical in shape; have varying densities and gravity fields; different spin rates and tumbling orbits; and may have physical surface features making them unsuitable for a human landing. The term human landing used in this paper does not necessarily imply a human physically walking on the surface due to very low gravity but rather, translating over the surface on umbilical tethers or with small propulsive devices. Without close inspection, the probability was estimated to be 70% that a candidate object might be suitable for a human landing based on the proportion of known asteroids with greatest scientific interest. In the present study there was no intermediate condition where an asteroid might be partially suitable--it would either be suitable or unsuitable for landing. The actual prior probability would be estimated from Earth-based observations when the final target set was determined.

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SEND A SURVEYOR?

If a surveyor was sent, it would return a positive or negative report for suitability from visual imaging, high resolution mapping, and radar measurements. Based on the historical successes of other survey missions in the solar system, the likelihood the surveyor would report a positive suitability if the surface was actually suitable was estimated at 95 percent. The surveyor would mistakenly report a positive suitability if the surface was not suitable with probability 5 percent (false-positive). The surveyor would correctly report a negative suitability if the surface was not suitable with likelihood 95 percent, and report negative suitability 5 percent of the time if the surface was actually suitable (false-negative).

If the report was positive after the surveyor rendezvous, a decision to go forward with the launch of the human mission would be taken. However, if the human mission was launched, there would remain uncertainty whether the surface was actually suitable or not suitable for the landing since the suitability detection capabilities (although very good) are not perfect. If the decision was not to launch the human mission, only the payoff associated with the surveyor would be incurred.

If the surveyor report were negative, the choice could be made to proceed with the human mission anyway since the quantity of science data gathered from a close encounter without landing is still believed to be significant. If the human mission launch proceeded, the outcome suitability would still be uncertain.

SEND A SECOND SURVEYOR?

There is another possibility--send a second surveyor mission to another asteroid if the report from the first surveyor was negative. Because the second surveyor would follow the first surveyor within a short time period, it is likely that the two spacecraft would be identical so the estimated likelihoods for the various outcomes described for the first surveyor would be the same. After the second surveyor report, the decision to launch or not launch the human mission would be reviewed. Note that the second surveyor would go to a different asteroid since the first asteroid was declared as unsuitable for landing. This distinction affects some of the probability calculations described below.

Note also that sending any surveyors that yielded positive reports followed by no human mission were inadmissible options. It was also assumed that if no surveyors were sent, the option to not send the human mission would also be inadmissible.

PAYOFFS

The productivity of each alternative in the study was computed from a measure of value divided by a measure of cost. Because the study was in the exploratory planning stages, costs for the alternatives had not formally been estimated. However, there were estimates of total mass delivered to orbit in metric tons, *t*, which historically have correlated with cost. In addition, the specific objectives and mission success criteria for these missions had also not been formally defined. As a result, 100% mission return from a landing by the human mission was used as the benchmark for the other alternatives. An estimate had been made by decision makers that a survey mission would only achieve 30% of the value of a human mission while a human mission that could not land would only obtain 70% of the value of a human mission that landed. It was further assumed that combinations of options would be additive in value. Table 1 summarizes the cost (mass), value (relative to the human landed mission), and productivity payoffs for the alternatives. Note that only the uncertainties associated with suitability for a human landing were addressed in this study—it was assumed that all of the missions in whatever combinations were enumerated would be successful.

Table 1. Payoffs Showing Cost (Mass), Value, and Productivity Estimates [6]

Alternative	Cost, t	Value (Percent)	Productivity Metric (value/t)
Surveyor only	0.5	30	60
Human Mission, No Landing on Asteroid	390	70	0.23
Human Mission, Landing on Asteroid	390	100	0.33

APPROACH

The question that initiated this study was whether the risk-reducing strategy of sending a surveyor before a human mission could be demonstrated quantitatively [1]? The elements of this problem suggested a classic Bayesian value of information approach since it allows the benefits of sending a surveyor to be quantified using the expected value of sample (suitability) information, EVSI [5] [8]. After a number of discussions with mission planners, a decision tree for this problem was developed with branches for the outcomes of each surveyor and four decision strategies: (1) send one surveyor before the human mission; (2) send one surveyor with an option for a second if the first was unsuitable; (3) send two surveyors at the same time; or (4) send no surveyors—send the human mission directly (see Figure 1). The branches of the tree were populated by the probabilities described above and by the posterior probabilities for the surveyor branches using Bayes theorem.

The optimal decision strategy was determined using backward induction to compute the expected value of each choice. The EVSI's were computed and compared to the human mission without surveyors to determine whether (and how many) surveyors should be employed to lower the risk of sending the human mission. The EVSI was computed from the following expression:

$$EVSI = \text{Expected Value with Surveyor Information} \\ - \text{Expected Value without Surveyor Information}$$

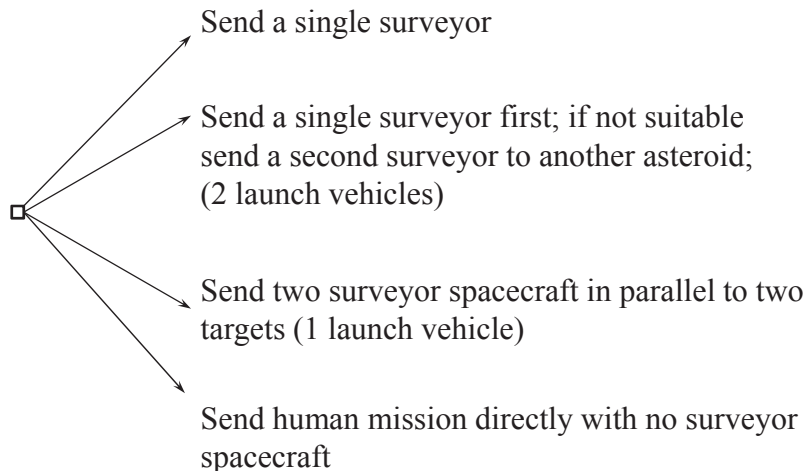


Figure 1. Decision Strategies for the Surveyor Problem

RESULTS

Based on maximization of productivity, the optimal strategy was to send two surveyors simultaneously to two asteroids. This was influenced primarily by the probability of suitability and the higher compound probability of at least one asteroid being suitable. The single surveyor case had a baseline probability of 0.70. The two mission case where the second mission occurred only if the first outcome was unsuitable had a probability at least one would be suitable of 0.79. The two mission case where both were launched at the same time had the highest probability at least one would be suitable of 0.91.

The EVSI results are summarized in Table 2.

Table 2. Expected Value of Surveyor Information (EVSI)
Showing Maximum Productivity with Two Surveyors Launched Simultaneously

Alternative	EVSI, (Value/Cost)
Single Surveyor	60.3
Single Surveyor with Potential Second Surveyor	79.5
Two Surveyors Sent At The Same Time	120.3
No Surveyors—Direct Human Mission	0.30

The low cost of the surveyors relative to the human mission made them inexpensive insurance against the risks of an unsuitable outcome. In probabilistic terms, the single surveyor case was analogous to tossing a single die to determine the suitability outcome; the two surveyor case with one surveyor followed by an optional second surveyor was analogous to tossing a single die once followed by the chance of tossing a second die if the outcome of the first was unsuitable. Sending two surveyors simultaneously was analogous to tossing two die at the same time with the correspondingly higher probability of at least one “success.”

While it was initially assumed that each alternative would achieve 100% success (no technical failures), the same probabilistic results would apply if the term “suitability” was replaced by “mission success.” That is, the ranking of surveyor strategies would be the same except the probabilities would be higher (e.g. the prior probability of mission success might be 0.95).

Because the prior probabilities were subject to debate, they were varied parametrically over a range of values. The value of the surveyor missions was also a point of contention because the argument was made that the surveyors had little inherent value (science or otherwise) to the human mission other than risk reduction. The EVSI’s were recomputed over a range of surveyor science values from the baseline of 30% down to 10% of the human mission. One parametric space for different prior probabilities and a surveyor value of 30% is illustrated in Figure 2. As the surveyor value was decreased toward 10%, the curves moved downward retaining the same conclusion in each case—send two surveyors at the same time.

DISCUSSION AND CONCLUSIONS

The use of a productivity measure based on relative value raised the question whether the conclusions might be different if actual estimates were used. The substitution of mass versus actual cost was not believed to be significant since mass has been shown to correlate with mission cost and used to that

effect [2] [5]. The large gap between the surveyor mass and human mission mass (0.5 t vs. 390t) is more important than the precise estimate of cost. In other words if costs were available, there would still be a very large gap between the values leading to the same conclusion. Questions regarding the value component of productivity were addressed by sensitivity analysis showing the conclusions to be invariant under large changes in assumed value. Nonetheless, previous work has developed and applied an improved measure of value based on science sampling and measurements that should be useful to this program as the science objectives are refined [7].

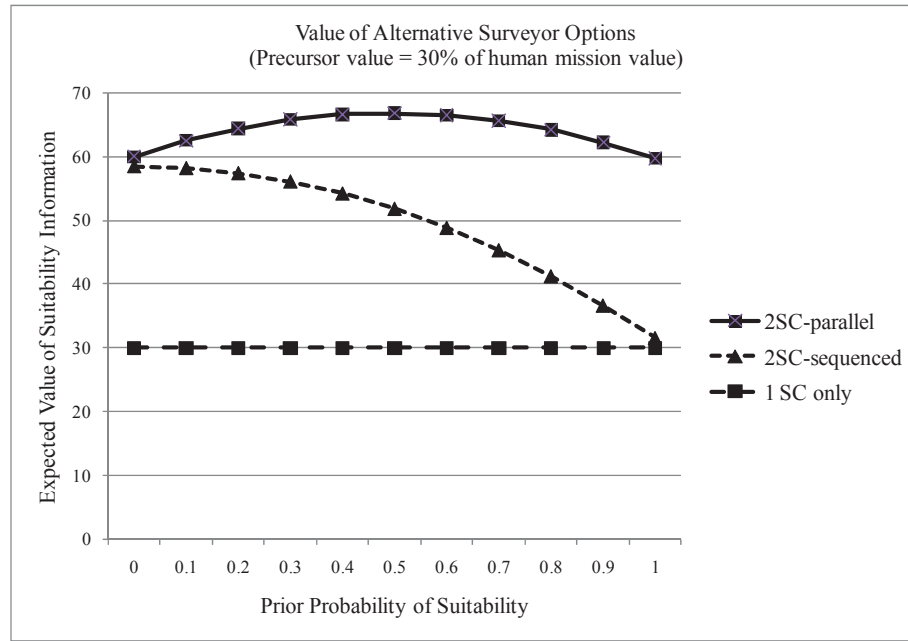


Figure 2. Prior Probability of a Suitable Landing versus EVSI Productivity
Showing Expected Value of Each Strategy Relative to no Surveyors

During this study a number of conclusions were drawn:

- This analysis supports the value of surveyor missions to asteroids, and indicates that one launch with two spacecraft going simultaneously to two independent targets seems optimal. The likelihood of finding a suitable target is substantially greater than with just a single launch, and the incremental productivity (using mass as a surrogate for cost) of going to three or more simultaneous spacecraft is not significant.
- The primary determinant of the optimal decision was the probabilistic structure of the sampling approach. The higher the overall probability of suitability along a decision tree branch, the larger the expected value of that branch and the resulting EVSI.
- The same ranking of surveyor strategies would follow if the surveyor problem were redefined to address mission success. The event “suitability” would be replaced by the event “mission success” and the prior probabilities of success would be estimated from reliability and historical estimates.
- The basic question about demonstrating the risk reducing benefit of the surveyors provide has been answered in this paper. There is value in sending the relatively inexpensive surveyors to confirm the suitability for the human landing and it has been shown quantitatively for a range of possible prior probabilities and surveyor value.

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